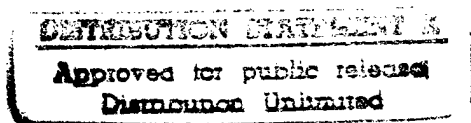


Serial Number 865,151
Filing Date 29 May 1997
Inventor Mark S. Peloquin

NOTICE

The above identified patent application is available for licensing. Requests for information should be addressed to:



OFFICE OF NAVAL RESEARCH
DEPARTMENT OF THE NAVY
CODE OCCC
ARLINGTON VA 22217-5660

19971119 012

[DTIC QUALITY INSPECTED 3

2
3 METHOD AND APPARATUS FOR FREQUENCY FILTERING
4 USING AN ELASTIC, FLUID-FILLED CYLINDER

5
6 STATEMENT OF GOVERNMENT INTEREST

7 The invention described herein may be manufactured and used
8 by or for the Government of the United States of America for
9 Governmental purposes without the payment of any royalties
10 thereon or therefor.

11
12 CROSS-REFERENCE TO RELATED PATENT APPLICATIONS

13 This patent application is co-pending with one related
14 patent application entitled "OPTIMIZING THE COMPRESSIONAL WAVE
15 ENERGY RESPONSE OF AN ELASTIC FLUID-FILLED CYLINDER" (Navy Case
16 No. 78034) by the same inventor as this patent application.

17
18 BACKGROUND OF THE INVENTION

19 (1) Field of the Invention

20 The present invention relates generally to frequency
21 filtering, and more particularly to a method and apparatus for
22 mechanically filtering in the frequency domain unwanted pressure
23 fields impinging on an elastic fluid-filled cylinder (such as

those used in towed arrays) using the elastic fluid-filled cylinder.

(2) Description of the Prior Art

Towed acoustic arrays are used in a variety of commercial and military applications. For example, towed arrays are used in seismic survey applications as well as in antisubmarine warfare applications. In general, a towed array is used to measure a pressure field propagating in a fluid environment. A towed array typically consists of a plurality of hydrophones encased within a fluid-filled elastic cylinder. The fluid used to fill the elastic cylinder is matched to the outside fluid environment so that pressure fields are not attenuated as they are transmitted from the outside fluid environment to the fill-fluid surrounding the hydrophones in the array.

The individual hydrophone channels respond to the entire frequency spectrum of pressure fields that exist in the ocean, i.e., frequencies up to tens of thousands of hertz. However, this range of frequencies is larger than the typical towed array can process effectively because an array has a maximum operating frequency above which it begins to alias energy. The Nyquist sampling criteria states that two samples per wavelength are needed in order to extract full amplitude and phase information about the signal being measured. Since the channel spacing in an array is fixed at a distance d , the relationship between channel spacing and the minimum wavelength λ_{MIN} of the pressure signal that can be measured is

$$d \leq \frac{\lambda_{MIN}}{2} \quad (1)$$

1 The relationship between wavelength, frequency and wave speed c
2 is

$$\lambda = \frac{c}{f} \quad (2)$$

3 Combining the above equations and solving for f_{MAX} which is the
4 maximum frequency that the array can process without aliasing
5 gives

$$f_{MAX} \leq \frac{c}{2d} \quad (3)$$

6 All energy above this maximum frequency must be filtered
7 electrically or mechanically in order to prevent aliasing.

8

9 SUMMARY OF THE INVENTION

10 Accordingly, it is an object of the present invention to
11 provide a method and apparatus that operates to filter out
12 unwanted pressure fields that impinge on a fluid-filled elastic
13 cylinder.

14 Another object of the present invention is to provide a
15 method and apparatus that operates as a low-pass filter to reduce
16 unwanted pressure fields measured by the hydrophones of a towed
17 array.

18 Other objects and advantages of the present invention will
19 become more obvious hereinafter in the specification and
20 drawings.

1 In accordance with the present invention, a method and
2 system are provided for frequency filtering compressional wave
3 energy. An elastic cylinder is filled with a fluid that is
4 selected based on a fluid density ρ_i and a dilatational wave
5 phase velocity c_i thereof. The elastic cylinder so-filled is
6 immersed in a fluid environment defined by a fluid density ρ_o and
7 a dilatational wave phase velocity c_o . When the elastic cylinder
8 so-filled is subjected to a compressional wave propagating in the
9 fluid environment, a first radial resonance frequency of the
10 elastic cylinder is controlled by the fluid density ρ_i and the
11 dilatational wave phase velocity c_i . For example, the first
12 radial resonance frequency increases when the fluid is selected
13 such that a product $\rho_i c_i$ is increased relative to a product $\rho_o c_o$.
14 The first radial resonance frequency decreases when the fluid is
15 selected such that a product $\rho_i c_i$ is decreased relative to a
16 product $\rho_o c_o$. If the fluid is selected such that a product $\rho_i c_i$ is
17 equal to a product $\rho_o c_o$, the first radial resonance frequency will
18 increase with an increase in the dilatational wave phase velocity
19 c_i relative to the dilatational wave phase velocity c_o . However,
20 if the fluid is selected such that a product $\rho_i c_i$ is equal to a
21 product $\rho_o c_o$, the first radial resonance frequency will decrease
22 with a decrease in the dilatational wave phase velocity c_i
23 relative to the dilatational wave phase velocity c_o . Further
24 tuning of the first radial resonance frequency can be achieved by
25 adjusting the radial wall thickness of the elastic cylinder.

BRIEF DESCRIPTION OF THE DRAWINGS

Other objects, features and advantages of the present invention will become apparent upon reference to the following description of the preferred embodiments and to the drawings, wherein corresponding reference characters indicate corresponding parts throughout the several views of the drawings and wherein:

FIG. 1 is a schematic of a pressure-field sensing array configured in accordance with the present invention;

FIG. 1A is a cross-sectional view through the array of FIG. 1;

FIG. 2 is a spatial representation of the displacement of the array's cylinder for the first radial resonance frequency thereof;

FIG. 3 is a graph of wavenumber k versus frequency ω for the fluid in the array's cylinder indicating the propagating and non-propagating regions of the wavenumber-frequency plane;

FIGS. 4A and 4B are graphs of the magnitude ratio as a function of frequency for a plurality of case simulations used to illustrate the present invention; and

FIG. 5 is a schematic of a pressure-field sensing array having a plurality of sealed cylinder segments, each of which is tuned for a specific first radial resonance frequency in accordance with the present invention.

1 DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

2 Referring now to the drawings, and more particularly to FIG.
3 1, a pressure-field sensing array is shown and is referenced
4 generally by the numeral 10. Array 10 consists of a sealed
5 elastic cylinder 12 filled with a fluid 14. Sealing of elastic
6 cylinder 12 at either end thereof can be accomplished with end
7 caps or bulkheads 16 and 18 as is known in the art. The length
8 of cylinder 12 is not limited. Maintained within cylinder 12 are
9 a plurality of hydrophones 20 spaced apart from one another along
10 the length of cylinder 12. Electronics (not shown) associated
11 with each hydrophone 20 can be included within cylinder 12 or can
12 be maintained on a host platform, e.g., onboard a ship 30, to
13 which array 10 is tethered. Typically, hydrophones 20 are
14 coupled to one another via communication lines 22, and are
15 further coupled to ship 30 over a tether/communication line 24.
16 A cross-sectional view of towed array 10 is shown in FIG. 1A.
17 The thickness of cylinder 12 is indicated at T_c . Hydrophone 20
18 and communication line 22 are centrally positioned in cylinder 12
19 and surrounded by fluid 14. In a typical scenario, array 10 is
20 immersed in a fluid environment 50, e.g, seawater, and is towed
21 therethrough by ship 30.

22 The characteristic impedance for dilatational wave (know
23 also as compressional wave) propagation in a fluid is given by
24 the quantity ρc , where ρ is the fluid density and c is the fluid
25 dilatational wave phase velocity. The inventive method and
26 apparatus described herein employs selective differences in the

1 density and dilatational wave phase velocity between fluid 14 and
2 fluid environment 50 to filter out the unwanted noise pressure
3 fields at frequencies above the frequency of the pressure waves
4 of interest. In other words, elastic cylinder 12 and fluid 14
5 function as a frequency filter. In this description, the density
6 of fluid 14 will be designated ρ_i , the dilatational wave phase
7 velocity in fluid 14 will be designated c_i , the density of fluid
8 environment 50 will be designated ρ_o and the dilatational wave
9 phase velocity in fluid environment 50 will be designated c_o .

10 In order to filter the unwanted pressure fields, the present
11 invention controls the first radial resonance frequency of
12 cylinder 12. The first radial resonance frequency places
13 cylinder 12 in a state of general vibration as shown in FIG. 2,
14 where the principle displacement is radial as indicated by the
15 vector labeled u_r . For impinging pressure fields at frequencies
16 above the first radial resonance frequency, cylinder 12 exhibits
17 decreased sensitivity. In general, the unwanted pressure fields
18 have a broad frequency spectrum that includes frequencies above
19 the first radial resonance frequency of a typical elastic
20 cylinder used in towed arrays. Thus, the present invention tunes
21 cylinder 12 in terms of its frequency sensitivity to optimize
22 dynamic performance of the array.

23 The mathematical space for discussing the present invention
24 is known as the wavenumber-frequency space or plane defined by
25 the relationship $k = 2\pi/\lambda$, where k is the wavenumber in
26 radians/meter and λ is the spatial wavelength of vibration.

1 Within the wavenumber-frequency plane, the pressure field in
 2 either fluid 14 or outer fluid environment 50 is characterized by
 3 two distinct regions, the propagating and non-propagating
 4 regions. The propagating region for inner fluid 14 is contained
 5 between the lines $k = \pm\omega/c_i$ and hatched as shown at 26 in FIG. 3.
 6 In propagating region 26, the radial variation of the pressure
 7 field follows the Bessel function of the first kind, and does not
 8 undergo decay with respect to radial position within cylinder 12.
 9 The remainder of the wavenumber-frequency plane comprises the
 10 non-propagating regions 28 where $|k| > |\omega/c_i|$. Pressure fields
 11 in non-propagating regions 28 impinging on the outer surface of
 12 cylinder 12 undergo an exponential decay. The decay follows a
 13 modified Bessel function where decay varies with respect to
 14 radial position within cylinder 12.

15 The magnitude of the inner fluid pressure field P_i ,
 16 normalized by the outer fluid pressure field magnitude P_o , is
 17 expressed in decibels (dB) according to the following equation

$$10 \log \left(\frac{P_i(r_1)}{P_o} \right)^2 \quad (4)$$

18 where r_1 is the radial distance from the central longitudinal
 19 axis of cylinder 12 at which the inner pressure field is
 20 evaluated. The mathematical derivation of the dynamic response
 21 is contained in "A Closed-Form Dynamic Elasticity Solution to the
 22 Fluid/Structure Interaction Problem of a Two-Layer Infinite
 23 Viscoelastic Cylinder With Inner and Outer Fluid Loading Subject

1 to Forced Harmonic Excitation," by M.S. Peloquin, NUWC-NPT
2 Technical Report 11,067, Naval Undersea Warfare Center, Newport,
3 Rhode Island, June 1996, the contents of which are hereby
4 incorporated by reference.

5 As mentioned above, the prior art attempts to match the
6 density ρ and dilatational wave phase velocity c of both fluid 14
7 and outer fluid environment 50 to prevent attenuation of pressure
8 fields. However, the present invention employs selective
9 differences between fluid 14 and outer fluid environment 50 in
10 terms of density and dilatational wave phase velocity to filter
11 out pressure fields that exist above the maximum frequency of the
12 array. Such filtering is accomplished by controlling or tuning
13 the first radial resonance frequency of cylinder 12. A reduction
14 in the first radial resonance frequency of cylinder 12 is
15 achieved by selecting a fluid 14 whose product $\rho_i c_i$ is less than
16 the product $\rho_o c_o$. Reduction of the first radial resonance
17 frequency can also be achieved when the product $\rho_i c_i$ is equal to
18 the product $\rho_o c_o$ provided the dilatational wave phase velocity c_i
19 is less than the dilatational wave phase velocity c_o .
20 Conversely, an increase in the first radial resonance frequency
21 is achieved by selecting a fluid 14 whose product $\rho_i c_i$ is greater
22 than $\rho_o c_o$. An increase in the first radial resonance frequency
23 can also be achieved when the product $\rho_i c_i$ is equal to $\rho_o c_o$
24 provided the dilatational wave phase velocity c_i is greater than
25 the dilatational wave phase velocity c_o .

1 By way of example, if outer fluid environment 50 is seawater
2 ($\rho_o = 1026 \text{ kg/m}^3$ and $c_o = 1500 \text{ m/sec}$) or fresh water ($\rho_o = 998$
3 kg/m^3 and $c_o = 1481 \text{ m/sec}$), fluids 14 that fit the general
4 constraints outlined above for increasing the first radial
5 resonance frequency include, for example, glycerin, castor oil,
6 ethanol amide, ethylene glycol, and glycerol. Examples of fluid
7 14 that fit the general constraints outlined above for decreasing
8 the first radial resonance frequency include, for example,
9 mercury, ethyl alcohol, turpentine, acetone, benzene, carbon
10 disulfide, carbon tetrachloride, chloroform, ethanol, ethyl
11 ether, kerosene, methanol, and nitrobenzene.

12 By way of further illustration, simulations were performed
13 to show how the present invention can be used to control or tune
14 the first radial resonance frequency over a fairly broad
15 frequency range. The details of the simulations are discussed in
16 the afore-mentioned Technical Report incorporated by reference
17 and will therefore not be presented herein. Briefly, the
18 simulations depict the dynamic response of a fluid-filled elastic
19 cylinder immersed in a fluid environment to a pressure impinging
20 on and normal to the outer surface of the cylinder. The exciting
21 pressure field is a traveling wave of arbitrary wavenumber k and
22 frequency ω and can be expressed mathematically as

$$P_o e^{i(kx - \omega t)} \quad (5)$$

23 where x is the longitudinal coordinate coincident with the
24 longitudinal axis of the cylinder, and t is time.

1 The simulations were performed for an outer fluid
2 environment similar to water, i.e., fluid density $\rho_o = 1000 \text{ kg/m}^3$
3 and dilatational wave phase velocity $c_o = 1500 \text{ m/sec}$. These
4 values were held constant for all cases of the simulations. The
5 properties of the simulated elastic cylinder were as listed below
6 in Table 1. Typically, the elastic cylinder is made from a
7 rubber or urethane material such as ESTANE 58881 or ESTANE 58886
8 available commercially from BF Goodrich. Other suitable
9 materials include melt-process rubbers such as ALCRYN 1160, 1180
10 or 3155 commercially available from DuPont.

Table 1: Properties of Simulated Elastic (e.g., ALCRYN) Cylinder

<u>Property</u>	<u>Value/Units</u>
Young's Modulus	$1.0 \times 10^8 \text{ N/m}^2$
Structural Loss Factor	0.3
Density	1070 kg/m^3
Poisson's Ratio	0.4
Inner Radius	1.2 inches
Outer Radius	1.5 inches
Radial Wall Thickness	0.3 inches

1 The first radial resonance frequency is controlled by
2 variations in fluid density ρ_i of the fill-fluid (i.e., fluid 14)
3 and dilatational wave phase velocity c_i of the fill-fluid. A
4 number of such variations and resulting first radial resonance
5 frequency are listed in Table 2 where Case 0 is representative of
6 the situation where the fill-fluid matches that of the outer
7 fluid environment, i.e., $\rho_i = \rho_o$ and $c_i = c_o$.

Table 2: Simulation Cases For Controlling First Radial
Resonance Frequency

FIGs. 4A/4B Reference					First Radial Resonance Frequency, Hz
<u>Case</u>	<u>Numeral</u>	<u>$\rho_i, \text{kg/m}^3$</u>	<u>$c_i, \text{m/sec}$</u>	<u>$\rho_i c_i$</u>	
0	100	1000	1500	1.5×10^6	2862
1	101	2000	3000	6.0×10^6	3140
2	102	2000	1500	3.0×10^6	3040
3	103	2000	750	1.5×10^6	2670
4	104	1000	3000	3.0×10^6	3090
5	105	1000	750	0.75×10^6	2233
6	106	500	750	0.375×10^6	1770
7	107	500	1500	0.75×10^6	2576
8	108	500	3000	1.5×10^6	2994
9	109	2000	500	1.0×10^6	2216
10	110	2000	1000	2.0×10^6	2876
11	111	666	3000	2.0×10^6	3040

1 The results of the simulations are displayed graphically in
2 FIG. 4 where the curves represent the magnitude ratio of the
3 inner-to-outer pressure field expressed as a decibel in
4 accordance with equation (1) recited above. Each curve is
5 referenced by the number associated therewith as indicated in
6 Table 2.

7 The goals of the present invention can also be accomplished
8 by varying the radial wall thickness T_r (see FIG. 1A) of cylinder
9 12 independent of the ρc relationship between fluid 14 and outer
10 fluid environment 50. More specifically, a decrease in first
11 radial resonance frequency is achieved by increasing radial wall
12 thickness T_r . Conversely, an increase in first radial resonance
13 frequency can be achieved by decreasing radial wall thickness T_r .
14 For example, for Case 0 in Table 2, the first radial resonance
15 frequency was 2862 Hz when $T_r = 0.3$ inches. Keeping all fluid
16 properties equal and changing T_r to 0.6 inches resulted in a
17 decrease in first radial frequency to 1960 Hz. Control of the
18 first radial resonance frequency in this manner can also be used
19 in conjunction with the variations in fluid 14 as described
20 above. The advantages of the present invention are numerous.
21 When used in a towed array immersed in a fluid environment, the
22 elastic cylinder and its fill-fluid can be tuned for a specific
23 first radial resonance frequency to filter out unwanted pressure
24 field frequencies. Such tuning can be achieved by selecting a
25 fill-fluid based on its fluid density and dilatational wave phase
26 velocity, by varying the radial wall thickness of the cylinder or

1 by a combination of fill-fluid choice and specified radial wall
2 thickness. The combination of selecting a fluid 14 based on its
3 ρ and c values along with a specified radial wall thickness T_r ,
4 provides great flexibility in tuning the first radial resonance
5 frequency of a fluid-filled elastic cylinder. In this way, the
6 cylinder and fluid act as a frequency filter that can be used,
7 for example, in towed arrays to optimize performance thereof.

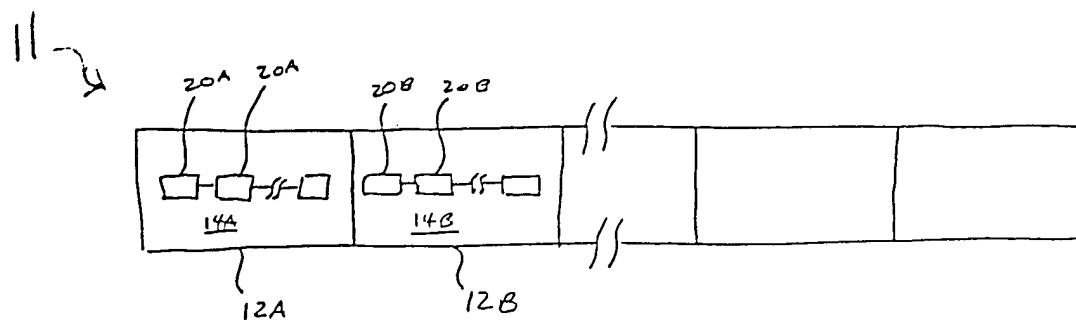
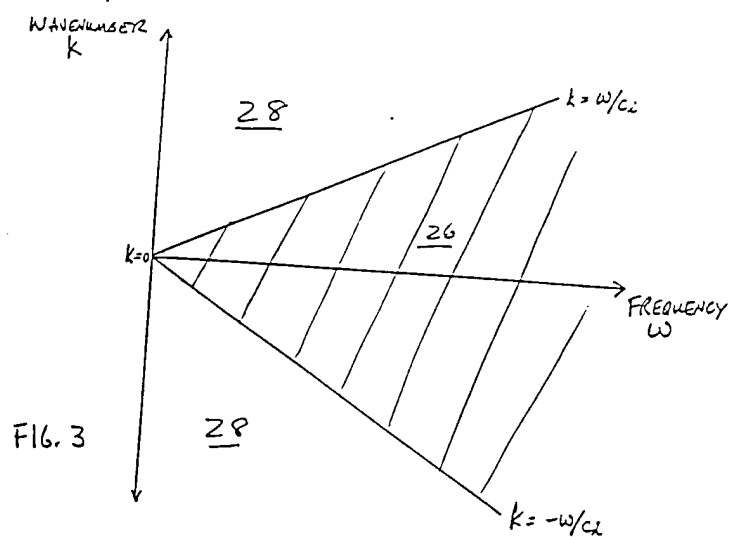
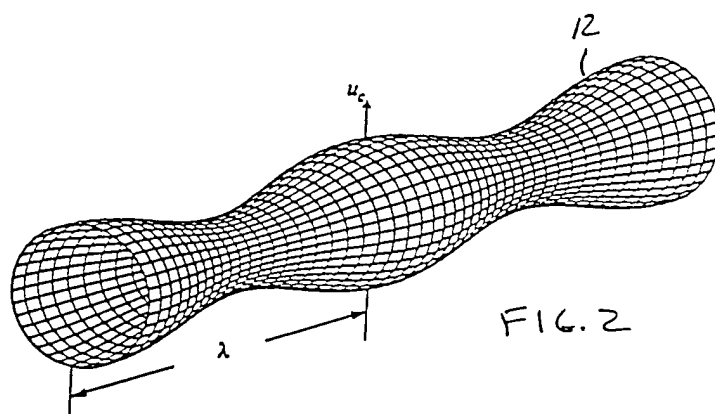
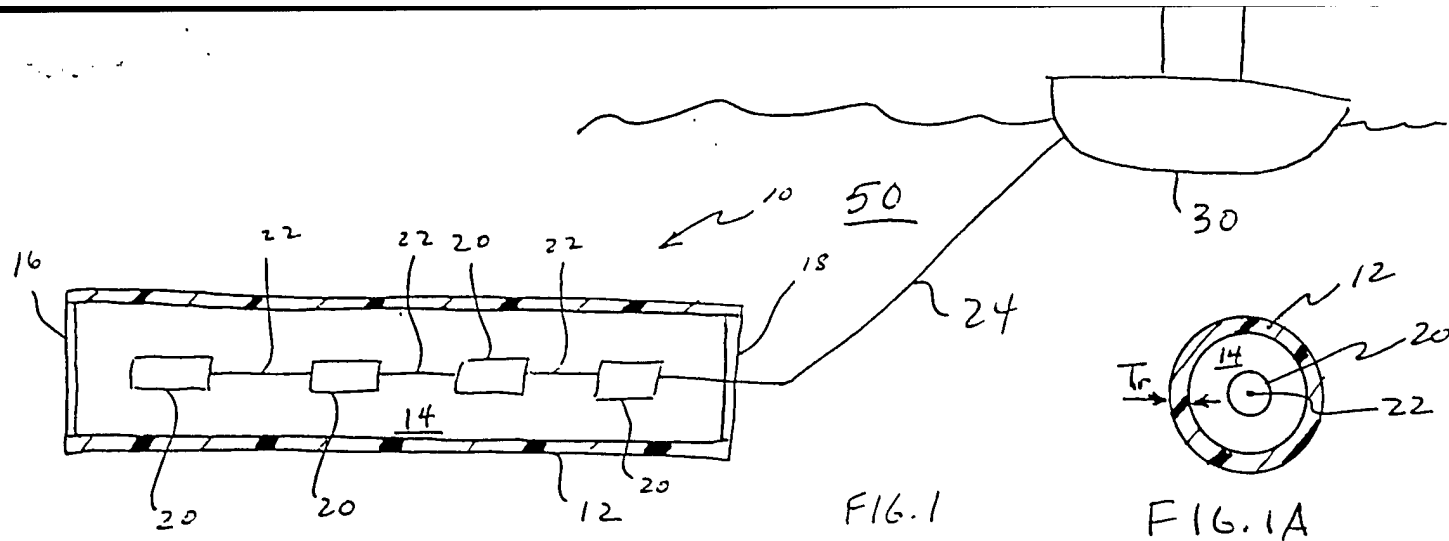
8 As shown schematically in FIG. 5, the present invention
9 could also be used to construct a pressure-field sensing array 11
10 having a plurality of sealed elastic cylinder segments 12A, 12B,
11 ... Housed within each cylinder segment is one or more
12 hydrophones 20A, 20B, ... Each cylinder 12A, 12B, ... can be
13 tuned to a specific first radial resonance frequency. Such
14 tuning is accomplished by selecting each cylinder's fill-fluid
15 14A, 14B, ..., by adjusting the radial wall thickness of each
16 cylinder, or by a combination of these two methods as described
17 above.

18 Thus, it will be understood that many additional changes in
19 the details, materials, steps and arrangement of parts, which
20 have been herein described and illustrated in order to explain
21 the nature of the invention, may be made by those skilled in the
22 art within the principle and scope of the invention,
23

2
3 METHOD AND APPARATUS FOR FREQUENCY FILTERING
4 USING AN ELASTIC, FLUID-FILLED CYLINDER

5
6 ABSTRACT OF THE DISCLOSURE

7 A method and system are provided for frequency filtering
8 compressional wave energy. An elastic cylinder is filled with a
9 fluid that is selected based on a fluid density ρ_i and a
10 dilatational wave phase velocity c_i thereof. When the elastic
11 cylinder so-filled is subjected to a compressional wave
12 propagating in a fluid environment, a first radial resonance
13 frequency of the elastic cylinder is controlled by the fluid
14 density ρ_i and the dilatational wave phase velocity c_i . Further
15 tuning of the first radial resonance frequency can be achieved by
16 adjusting the radial wall thickness of the elastic cylinder.



MAGNITUDE

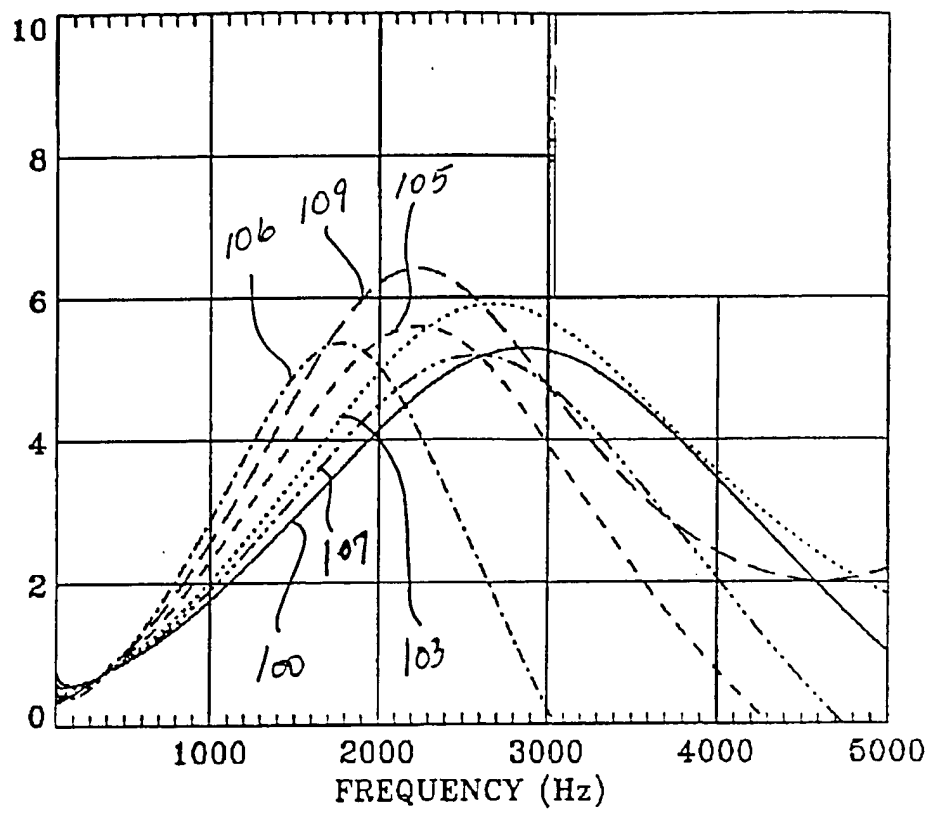


FIG. 4A

MAGNITUDE

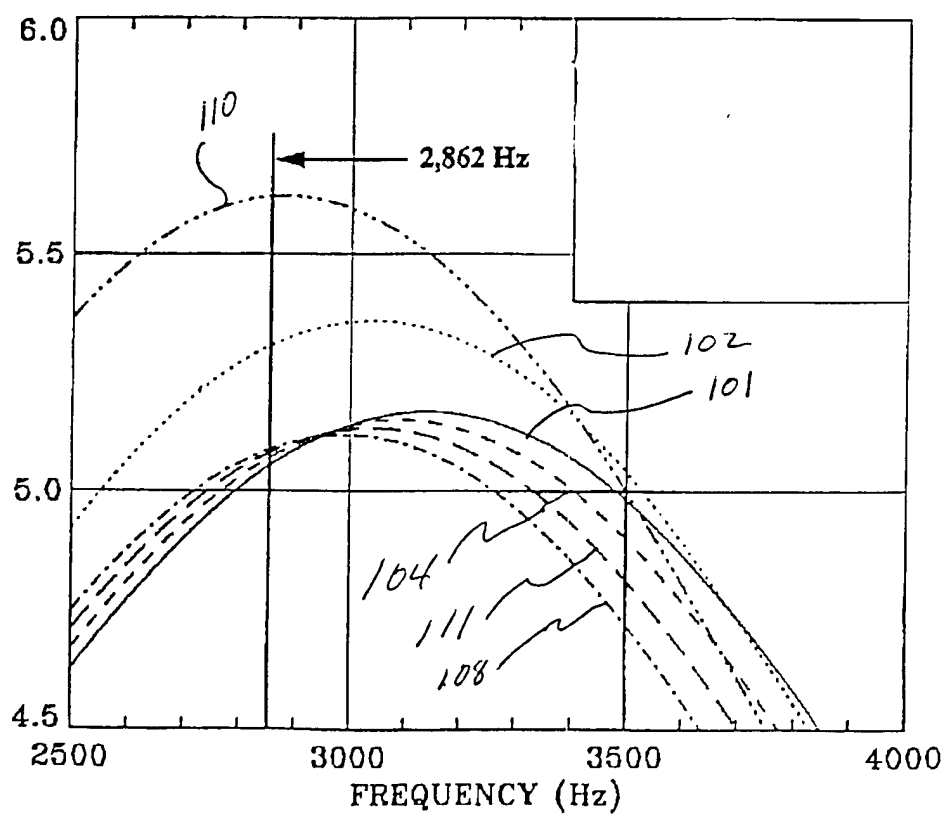


FIG. 4B